

From RHIC to LHC

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Measurements of the nuclear modification factor of inclusive yields of π^0 , $p\bar{p}$, non-photon electrons and prompt photon measured at RHIC are reviewed. Some of the difficulties arising from interpretation of these measurements such as similarity of the suppression pattern of light and heavy quarks, quarks and gluons, light quarks and prompt photon are discussed. The potential of two-particle and prompt photon correlation technique to unravel some of these open questions is presented. An emphasis is given to the influence of partonic transverse momentum on the prompt-photon correlations. The smearing between the trigger photon and back-to-back jet at LHC energy is discussed.

1. Introduction

A vast number of experimental results from the Relativistic Heavy Ion Collider (RHIC) changed, in many aspects, our understanding of ultra-relativistic nuclear collisions. High- p_T particle suppression observed in central $Au + Au$ collisions (*e.g.* [1]) and its absence in $d + Au$ collisions (*e.g.* [2]) where no excited nuclear medium exists provides quite firm indication of the final state interaction induced by a deconfined QCD medium [3]. Excessive production of baryons at intermediate p_T [4] is often interpreted as another manifestation on the deconfined medium. The dense partonic medium does not hadronize in the usual way of jet fragmentation, but partons rather recombine forming the baryon wavefunction directly. This so called “coalescence” mechanism [5] is quite successful in explaining many of the RHIC observations like ordering of azimuthal anisotropy parameter v_2 ([6] and references therein).

Although the theoretical interpretation of above mentioned phenomena is quite successful, many open questions still remain to be answered. Some of the most important are how exactly partons are losing their energy when they interact with deconfined QCD medium, where is this energy going to, how does the QCD medium modify

the parton properties, fragmentation process and many others.

2. Inclusive yields

Most successful models of partonic energy loss (GLV [7], BDMPS [8], Wang [9] and others) are exploring the inelastically induced gluon radiation process. These models are quite successful in describing the nuclear modification factor R_{AA} defined as ratio of inclusive particle yield in heavy ion collision to the binary collision scaled yield in $p + p$ data. However, T. Renk and K. Eskola in [10] studied the sensitivity of the R_{AA} parameter to the details of parton interaction with QCD medium. They argued that due to the strong quenching the particles reaching the detector may be radiated from the jets originating close to the surface of the QCD medium and those produced deep in the medium are fully absorbed. In this case the sensitivity of R_{AA} to the detailed modeling of the parton energy loss is reduced. In this light it is not surprising that predictions from other models *e.g.* [11] introducing different mechanism of gluon radiation are also able to reproduce measured values of R_{AA} . It is evident that more complex observables like two-particle correlations or reconstructed jets properties has to be explored.

Another open question arose from the analysis of the non-photonic electron yield originating from heavy (charm and bottom) quark fragmentation [12,13,14]. Induced radiation from heavy non-relativistic quarks is expected to be weakened by the dead-cone effect [15]. However, high- p_T e^\pm suppression seems to be as strong as it is in the case of light, u and d quarks. One of the possible explanations is that quarks are losing a significant fraction of their energy also via elastic $2 \rightarrow 2$ processes [16] often referred as collisional energy loss. Since the collisional energy loss plays obviously more important role for heavier partons it can compensate for the weaker radiational energy loss. However, this mechanism should be accompanied by significant broadening of the away-side hadron azimuthal distribution [17,18] which is not yet seen in the data [19]. An alternative model of heavy quark quenching, which does not require any broadening, attributes the quenching pattern to the hadronic rather to partonic interaction [20]. Authors of this model argue that the formation time of D and B mesons, on the order of 1 fm, is much shorter than formation time of π^0 particle and thus the suppression pattern is due to the dissociation of fully formed charmed mesons in contrast to π^0 formed outside the interaction region.

Another surprise comes from the similarity of R_{AA} measured for π^\pm and p/\bar{p} particles [21]. pQCD calculations indicate that a large fraction of p/\bar{p} baryons at high- p_T are produced from gluons unlike pions produced more by valence quark interactions. Suppression factors for quark and gluon are expected to be different because of different colored charge ($C_A/C_F=9/4$) [22]. However, the measured values of π^\pm and $p\bar{p}$ R_{AA} presented in [21] are almost identical in the $p_T \geq 5-6$ GeV/ c .

The prompt photon measurement presented by the PHENIX experiment [23] is certainly one of the most interesting results at RHIC. At sufficiently high- p_T prompt photons production is dominated by Compton scattering ($q + g \rightarrow q + \gamma$) and to some extent by $q\bar{q}$ annihilation, bremsstrahlung process and quark fragmentation. Photons are blind to the final state interaction and thus no nuclear modification is expected.

However, the preliminary data of PHENIX [23] reveals quite significant suppression in the $p_T \geq 15$ GeV/ c region.

Although the direct measurement of nuclear shadowing at RHIC energies is not yet available, it is not likely that the suppression of the prompt photon yield by a factor of two at $p_T \approx 18$ GeV/ c could be due to the shadowing [24]. Also the isospin effect (colliding nuclei contain protons and neutrons, however, nuclear data are compared to the yield in $p+p$ and it is known that photo-production cross section in $p+p$ and $n+n$ are slightly different) can explain some part of the high- p_T suppression, but certainly not all.

It is evident that for deeper understanding of parton interaction with excited nuclear medium an exploration of more exclusive processes like two particle, di-jet and γ_{direct} -jet correlations is needed.

3. Trigger-particle associated yields

It has been discussed that one of the unsettled questions related to the high- p_T particle quenching is what fraction of energy partons are losing via the radiative energy loss and what fraction is purely collisional. One of the possible ways to shed more light on this question is to study the modification of the fragmentation function as suggested *e.g.* in [25,11]. The LHC era with yet larger hard-scattering cross section opens the new regime of heavy ion physics allowing to explore the fully reconstructed jets and their properties. However, due to the large particle multiplicity produced in heavy ion collisions the reliable jet reconstruction is possible only at relatively high transverse momenta above 50 GeV or more. In order to explore the “low”- p_T region where the jet reconstruction is not possible the two-particle correlation technique can be used. However, extraction of underlying parton properties from two-particle correlation functions is not an easy task. For example, it has been believed for decades that the shape of the high- p_T trigger hadron associated x_E distributions, where

$$x_E = -\frac{\vec{p}_{Tt} \cdot \vec{p}_{Ta}}{p_{Tt}^2} \simeq -\frac{z_a \hat{p}_{Ta}}{z_t \hat{p}_{Tt}} \quad (1)$$

and \hat{p}_{Tt} , \hat{p}_{Ta} , p_{Tt} , p_{Ta} are the transverse momenta of the trigger and associated parton, trigger and associated hadrons and $z_a = p_{Ta}/\hat{p}_{Ta}$ and $z_t = p_{Tt}/\hat{p}_{Tt}$, reflect the shape of the fragmentation function. However, it has been demonstrated in [26] that the fixed momentum of the trigger particle p_{Tt} does not fix the mother parton momentum \hat{p}_{Tt} and it varies with p_{Ta} . In this case both z_a and z_t vary with p_{Ta} and this variation completely masks the actual shape of the fragmentation function.

One of the alternative ways to explore the fragmentation function is to study the particle distributions associated to the prompt photon. In the high- p_T region where the photo-production is dominated by the reverse Compton scattering diagram, the prompt photon balances the back-to-back quark. In such a case the measurement of the photon energy determines also the outgoing quark energy and thus the measurement of transverse momentum distribution of particles associated to the prompt photon corresponds to the measurement of the fragmentation function. However, also in this case there are important effects which need to be taken into account. One constraint comes from the fact that at low p_T the prompt photon production may be contaminated by fragmentation photons from the large number of gluonic jets produced in heavy ion collision [27]. Fragmentation photons obviously do not balance the away-side parton.

Another constraint comes from the fact that even when considering the leading order Compton diagram there is always soft QCD radiation which breaks the jet-photon momentum balance and the azimuthal collinearity. As a result of soft QCD radiation This non-perturbative radiation manifests itself as a non-zero value of the net parton-photon pair transverse momentum magnitude $p_{T\text{pair}}$. Originally this soft radiation induced transverse momentum was attributed to the individual incoming partons and the notation of k_T (parton transverse momentum) was introduced by Feynman, Field and Fox [28].

As discussed in [26] the k_T may be viewed as a sum of three different contributions:

- Intrinsic parton Fermi-momentum [28].

- Soft QCD radiation [29].
- Hard NLO radiation.

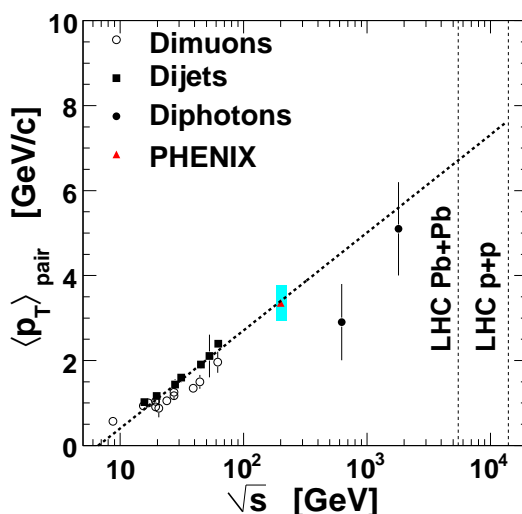


Figure 1. The net dimuon (open circles), dijet (solid squares), diphoton (solid circles) and back-to-back partons (red triangle) transverse momenta measured at various center of mass energies (see [30] and [26]). PHENIX back-to-back parton value is derived from dihadron acoplanarity when the average trigger hadron momentum fraction z_t is taken into account.

The magnitude of Fermi-momentum (truly intrinsic parton momentum) is determined by the transverse size of colliding nucleons and it is of order of 300 MeV/c. The large values of $\sqrt{\langle k_T^2 \rangle} \approx 3$ GeV/c at RHIC indicates that the soft and hard radiation are the dominant contributions. It evidently implies that it would be more appropriate to talk about the net pair transverse momentum rather than about k_T attributed to individual partons. However, we will stick to the

historical notation of Feynman ¹ *et al.*.

The net back-to-back parton transverse momentum $p_{T\text{pair}}$ induced by three different contributions discussed above will lead to the imbalance of the prompt photon and quark energies. One way of overcoming the constraint is to trigger on photon momenta much larger than the actual value of k_T . Extrapolation from measured values of $\sqrt{\langle k_T^2 \rangle}$ to LHC energy regime

$$\langle p_T \rangle_{\text{pair}} \approx \log(0.15 \cdot \sqrt{s})$$

(see Fig. 1) leads to the values larger by factor of two ($\langle p_T \rangle_{\text{pair}} = 7.7$ GeV/c and $\sqrt{\langle k_T^2 \rangle} = 6.1$ GeV/c at $\sqrt{s} = 14$ TeV) as compared to RHIC. If this will be the case at LHC energy then for the unbiased region of prompt photon momenta where the $\langle p_T \rangle_{\text{pair}}$ will be negligible lies probably way above $p_{T\gamma} \geq 20$ GeV/c.

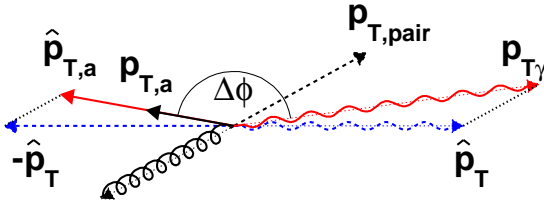


Figure 2. Schematic view of Compton $q + g \rightarrow q + \gamma$ photo-production event in the plane perpendicular to the beam. In purely leading order and in the center of mass of the hard scattering, the outgoing photon and quark (blue arrows) are exactly back-to-back. The soft QCD radiation, represented by single gluon line, leads to the acoplanarity and imbalance between the photon, $p_{T\gamma}$ and quark, $\hat{p}_{T,a}$ momenta.

In order to evaluate an effect of k_T imbalance more quantitatively let us consider the cartoon of hard scattering in the transverse plane

¹in the case of 2D Gaussian distribution there is a trivial relation $\langle k_T^2 \rangle = \frac{\pi}{2} \langle p_T \rangle_{\text{pair}}$

as shown on Fig. 2. In the center of mass of the hard scattering and in purely leading order Compton $q + g \rightarrow q + \gamma$ the outgoing photon and quark are exactly back-to-back having momenta \hat{p}_T and $-\hat{p}_T$. However, due to the QCD radiation discussed earlier the quark+photon system acquire a boosted in transverse direction along the $p_{T\text{pair}}$ vector and photon of momentum $p_{T\gamma}$ and quark $\hat{p}_{T,a}$ are emitted. Quark of momentum $\hat{p}_{T,a}$ fragments and particle of momentum $p_{T,a}$ is detected. We assume that the invariant mass of the $q + \gamma$ system before and after the $p_{T\text{pair}}$ boost is the same and thus

$$(\hat{\mathbf{p}}_{T,a} + \hat{\mathbf{p}}_{T\gamma})^2 = 2\hat{p}_{T,a}p_{T\gamma} - 2\hat{p}_{T,a}p_{T\gamma} \cos \Delta\phi = 4\hat{p}_T^2$$

It is known that the magnitude of $p_{T\text{pair}}$ has a Gaussian distribution. For example the muon pair transverse momentum distributions measured at $p_{\text{beam}} = 400$ GeV/c fixed target experiment [31] have clearly Gaussian shape in $p_{T\text{pair}} \leq 3$ GeV/c with a hint of power law tail due to the NLO contribution at $p_{T\text{pair}} \geq 3$ GeV/c. Assuming the Gaussian distribution for $p_{T\text{pair}}$ magnitude one can evaluate the production probability of quark-photon pair with $p_{T\gamma}$ and $\hat{p}_{T,a}$ given $\langle p_T \rangle_{\text{pair}}$ and \hat{p}_T (see Fig. 2) as

$$\mathcal{P}(\hat{p}_{T,a} \& p_{T\gamma}) \Big|_{\hat{p}_T} = \frac{p_{T\gamma} + \hat{p}_{T,a}}{\pi\sigma^2 \sqrt{\hat{p}_{T,a}p_{T\gamma} - \hat{p}_T^2}} \times \quad (2)$$

$$\times \exp \left[-\frac{(p_{T\gamma} + \hat{p}_{T,a})^2 - 4\hat{p}_T^2}{2\sigma^2} \right]$$

where $\sigma^2 = \langle k_T^2 \rangle$. It is then straightforward to integrate Eq. (2) over \hat{p}_T (here we assumed as in [26] $dN/d\hat{p}_T \propto \hat{p}_T^{-7}$) and fold with parametrized final state parton spectrum and fragmentation function as discussed in [26] to evaluate the prompt photon associated spectra.

Fig. 3 shows associated parton distributions calculated according Eq. (2) to the trigger photon of momentum $p_{T\gamma} = 5, 10$ and 25 GeV/c and $\sqrt{\langle k_T^2 \rangle} = 6$ GeV/c. At high- $p_{T\gamma}$ region where $p_{T\gamma} \gg k_T$ the associated parton distribution can be approximated by the Gaussian function centered at $p_{T\gamma}$ and of variance $\sigma^2 = \langle k_T^2 \rangle / 2$ (dashed curves on Fig. 3). More details can be found in [26].

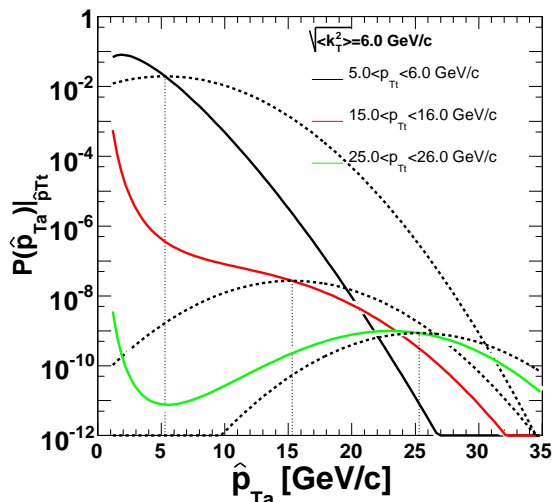


Figure 3. Associated parton distributions according integral of Eq. (2) to the trigger photon of momentum $p_{T\gamma}=5, 10$ and 25 GeV/c (black, red and green solid lines) and $\sqrt{\langle k_T^2 \rangle}=6$ GeV/c. Dashed lines represent the asymptotic Gaussian functions discussed in the text. Vertical dashed lines represent the trigger photon energies.

4. conclusion

It is evident that at LHC one can expect that the imbalance due to the k_T smearing completely washes out the correlation between the quark and photon energies for the photon energy below 10 GeV/c and the distributions deviate from the Gaussian function quite significantly even at $p_{T\gamma}=15$ GeV/c. In order to extract the fragmentation function from the prompt photon associated distributions in the $p_{T\gamma}$ region below 30 GeV/c at LHC the detailed understanding of k_T phenomena is necessary.

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